Excitation of Nuclear Isomers by γ Rays from ⁶⁰Co (Commemoration Issue Dedicated to Professor Sakae Shimizu on the Occasion of his Retirement)

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Excitation of Nuclear Isomers by γ Rays from ^{60}Co

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Long-lived isomeric states in stable nuclei ^{111}Cd and ^{115}In have been excited by the Compton-scattered γ rays from ^{60}Co. The flux of the scattered photons at resonance has been calculated in the single-scattering approximation. Using the observed γ activities of ^{111m}Cd and ^{115m}In and the calculated photon flux, the integral cross sections for the isomer production by photoexcitation of ^{111}Cd and ^{115}In have been evaluated to be $(3.5\pm0.4)\times10^{-25}$ cm$^2\cdot$ eV and $(1.9\pm0.1)\times10^{-25}$ cm$^2\cdot$ eV, respectively.

KEY WORDS Photoexcitation / Single-scattering approximation / Isotopes ^{111}Cd and ^{115}In /

I. INTRODUCTION

The excitation of nuclei by photons is one of resonance phenomena, that is, only the photon whose energy is just the difference between an excited level and the ground state of the nucleus can excite it. The excited nucleus emits radiations in the course of de-excitation, but generally it is difficult to detect this radiation during the photon irradiation because of strong backgrounds due to primary photons. However, the observation of this phenomenon is possible due to the existence of a finite branching ratio between the photo-excited level and a low-lying metastable state which permits detection of the induced isomer activity after the photon source is removed.

The experimental evidence of this process was established by Pontecorvo and Lazard[1] and Collins *et al.*[2] in 1939. They produced the metastable state of ^{115}In by irradiation with x rays from the accelerator and studied the energy of the excited level. Harbottle[3] observed the production of nuclear isomer of ^{115}In by the Compton-scattered γ photons from the radioactive sources. Yoshihara and Ikeda[4] studied the photoactivation process of ^{87}Sr, ^{103}Rh, ^{107,109}Ag, ^{111}Cd, ^{113,115}In, and ^{176}Lu using ^{60}Co sources and determined the over-all cross sections for these nuclides. Veres and his collaborators[5] also measured the activation cross sections of ^{77}Se, ^{79}Br, ^{167}Er, ^{195}Pt, and ^{199}Hg, in addition to nuclides mentioned above.

In the field of nuclear physics, the photo-nuclear excitation process has been used as a tool for nuclear spectroscopy. The usefulness of photons as a probe of the electromagnetic structure of excited states of nuclei is well known and the advantage of photoexcitation over other excitation mechanisms is that the interaction is purely electromagnetic. The photoexcitation probability strongly depends on the gross features of the upward transition, such as the changes in energy, angular momentum, and parity, and

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it is possible to obtain the various informations about the transition and the electromagnetic structure of the excited levels. Booth *et al.*[6,7] and Boivin *et al.*[8,9] measured the integral cross sections for excitation of ^{77}Se, ^{87}Sr, ^{107,109}Ag, ^{111}Cd, ^{113,115}In, and ^{199}Hg by bremsstrahlung radiation. They estimated spins, parities and level widths of the excited levels from their results.

In order to estimate the activation cross section from the induced activity, Yoshihara[10] derived the formulae for the photon flux in different geometrical shapes of γ-ray sources, based on the assumption that the direction of the scattered photon is the same as that of the primary γ ray. However, this assumption is not reasonable, because the number of the scattered photons incident upon the target depends on both the scattering point and the scattering angle. This means that the angular distribution of secondary photons cannot be ignored.

Experimentally, all the measurements by ^{60}Co sources have been performed with poor-resolution detectors, such as NaI(Tl) crystal and proportional counter. Considering low induced activity in the photoexcitation process, it is advantageous to investigate this process by the use of high-resolution detector.

In the present work, we calculated the flux of the scattered photons at the target by taking into account the scattering angle of γ rays. Experimental studies on photoexcitations of ^{111}Cd and ^{115}In by the ^{60}Co γ rays were carried out with a Ge(Li) detector and the cross sections of these nuclei were estimated from the observed activity and the calculated flux of photons.

II. EXPERIMENTAL

The present experiment has been performed by using the ^{60}Co irradiation facility of the Institute for Chemical Research of Kyoto University.[11] The radiation source consists of twenty ^{60}Co pellets and the dimension of each source is 3.6-mm diam by 240-mm length. The total activity is 594 Ci (August, 1978). Irradiations were performed at the center of the sample chamber in air and targets were supported by the thin lucite plate so as to keep the fixed irradiation geometry. The distance between the target and the central axis of the source is 10.2 cm. The dose rate at the irradiation point was measured by using the glass dosimeter and found to be 4.75×10^4 R per hour.[11]

The size of the In foil is 2.0-cm diam by 0.054-cm thick, while the Cd target is composed of four disks, each of which is 2.0-cm diam by 0.050-cm thick. Weights of target materials are 1.24 g for In and 5.46 g for Cd. These targets were irradiated for period exceeding ten times of the half-life of the metastable state.

In the energy region lower than the higher γ ray from ^{60}Co (1333 keV), the energies of levels, which can be excited by photons and cascade down to the isomeric states, are known to be 1078 keV for ^{115}In[7] and 1300 keV for ^{111}Cd.[5] The 1078-keV state in ^{115}In decays to the 336-keV isomeric state. On the other hand, the 1300-keV state in ^{111}Cd feeds the transition to the 396-keV isomeric state, from which two γ rays, 151 and 245 keV, are emitted in cascade.

The 336-and 245-keV γ rays from the isomeric states of ^{115}In and ^{111}Cd were measured with a 75-cm^3 Ge(Li) detector. The resolving power of this detector is 1.44 keV

(FWHM) for 276-keV γ ray from ^{133}Ba. Because of the low activity induced in the targets, the Ge(Li) detector was surrounded with the 1-cm brass plates and 10-cm lead blocks to reduce the natural backgrounds. The output pulses from the detector were feeded into the minicomputer PDP 11/04.

The detection efficiency of the Ge(Li) detector was determined by using the several radioactive sources ^{109}Cd (88.036 keV), ^{114m}In (190.274 keV), ^{203}Hg (279.188 keV), and ^{113}Sn (391.688 keV), where the values in the parentheses show the energies of γ-ray photons provided by Heath.[12] These sources have a disk shape, the radius of which is equal to that of targets. The absolute intensities of these sources were measured with the 2″ × 2″ NaI(Tl) scintillation counter and the detection efficiencies of the Ge(Li) detector were determined for γ rays with the energies mentioned above. By interpolating the measured values, we found the detection efficiencies for the 336-keV photons emitted from ^{115m}In and the 245-keV photons from ^{111m}Cd to be $(3.6\pm0.1)\times10^{-2}$ and $(4.8\pm0.1)\times10^{-2}$, respectively.

The relation between the channel number of the pulse height analyzer and the energy of γ rays is calibrated by the least-squares method using standard radioactive sources; ^{57}Co (122.060±0.010 keV and 136.471±0.010 keV), ^{203}Hg (279.188±0.006 keV), and ^{137}Cs (661.638±0.019 keV), where the values of the γ-ray energies were taken from Ref. 12. From this relationship, the energies of γ rays emitted from the isomeric states were determined as 150.6±0.4 keV and 245.3±0.4 keV for ^{111}Cd and 336.7±0.4 keV for ^{115}In. The typical spectrum of γ rays emitted from cadmium is shown in Fig. 1.

The half-lives of nuclear isomers were evaluated from the decay curves by the least-squares method and found to be 49.7±4.3 min for ^{111m}Cd and 4.47±0.07 hour for ^{115m}In. These experimental values are in good agreement with the literature values.[13,14] Figure 2 shows the decay curve of the isomeric state of indium.

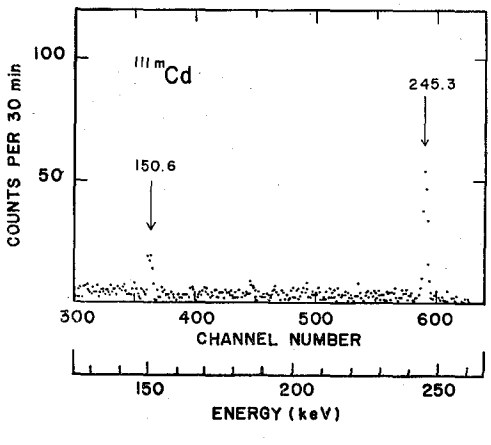

Fig. 1. Observed spectrum of γ rays from cadmium foils after irradiation by γ rays in a 600-Ci ^{60}Co irradiation facility.

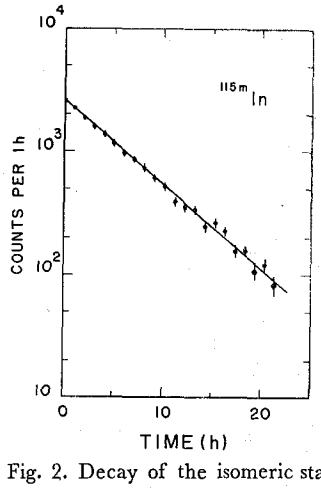

Fig. 2. Decay of the isomeric state of ^{115}In irradiated by ^{60}Co photons.

III. CALCULATION OF PHOTON FLUX

In order to determine the cross section for photoexcitation, Yoshihara[10] assumed for the case of a cylindrical ^{60}Co source that (a) the activity is uniformly distributed at the central axis of the source, (b) the target is regarded as a point, and (c) the scattered photons do not change their directions. He derived a formula for the photon flux at target as

$$N_r' = \int_0^H a_0 n\phi \exp[(\mu_1-\mu_2)\, y] \frac{1-\exp(-\mu_1 y)}{\mu_1} \frac{\exp(-\mu_1 y)}{4\pi[D^2+(x-h)^2]} dx, \qquad (1)$$

and

$$y = \frac{[D^2+(x-h)^2]^{1/2}}{D} \frac{d}{2}, \qquad (2)$$

where n is the electron density of the source material, a_0 is the source intensity per unit length, ϕ is the Compton-scattering cross section, μ_1 and μ_2 are the total attenuation coefficients for primary and scattered photons, D is the distance between the central axis and the target, h is the height of the target point, d is the source diameter and H is the source length. His model is schematically shown in Fig. 3(a). This formula has been widely employed to estimate the flux of scattered photons in the ^{60}Co irradiation facility. Veres[15] also used this formula to evaluate the cross sections for nuclear excitation by photons.

In the present work, we have considered the angular distribution of scattered photons. The problem of interation of photons with matter can be treated with the Boltzman transport equation by taking boundary conditions into consideration, in principle. However, because of practical difficulty in solving this type of equation in complex geometries, several approximation methods or Monte Carlo methods have been developed. We have attempted to estimate the scattered-photon flux in the single-scattering appro-

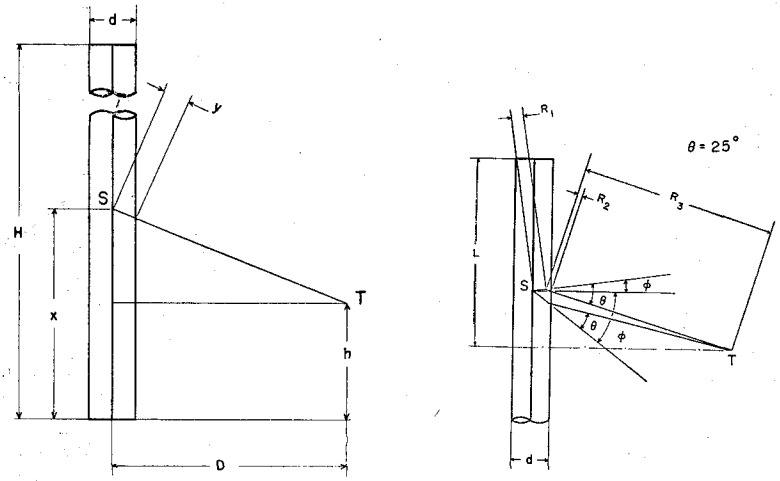

Fig3. Schematic illustration of geometrical relation for the calculation of γ-ray scattering; (a) Yoshihara's model and (b) the present work.

ximation. In this approximation, only the single-scattered photons are taken into account and the multiple scattering is ignored. Such a simple method, if reasonable, would be very useful in calculating the photon flux. This approximation was used by Trubey[16] for the air-scattered flux and dose rate of γ rays, and his results were in good agreement with those of Monte Carlo calculation.

In the present case, the single-scattering model is considered to be a good approximation, because the activation levels of both ^{111}Cd and ^{115}In are populated in the energy region higher than 1 MeV and the energy of photons scattered more than once is too low to activate the nucleus. In the calculation of the scattered flux, we used the following assumptions;

(1) the source is assumed to be a line,
(2) photons emitted from the source will be scattered only inside the stainless-steel cylinder covering the source,
(3) multiple scattering is neglected (single-scattering approximation),
(4) the effect of photon attenuation in air is ignored,

and

(5) the target is regarded as a point.

In our irradiation geometry, the distance between the center of target and the central axis of photon sources is 10.2 cm and the radius of the source cylinder is 0.18 cm. This means that the source can be considered as a line.

Sources of the scattered photons may be ascribed to the following four; the radioactive source itself, air between the source and the target, the wall surrounding the source, and the target. Total attenuation in air was estimated in the case of the photon energy of 1 MeV and the path length of 15.75 cm, which corresponds to the distance between the end point of the source and the target. Provided that the total attenuation coefficient of air is 8.22×10^{-5}cm^{-1} for the 1-MeV photon,[17] the attenuation factor in air is estimated to be 0.13%. This indicates that the scattering in air can be ignored and the assumption (4) is reasonable.

The photon scattered from the surrounding wall should pass through the region of the source pellets before entering the target. This photon has a large probability to be scattered once more in the source region and, if scattered twice, its energy would be insufficient to excite the target nucleus. By this reason, the contribution from the photons scattered in the wall is considered to be negligible.

The effect of scattering in the target was estimated by the same way as in the case of air. The total attenuation coefficient of cadmium for 1.30-MeV photon is 0.431 cm^{-1} and that of indium for 1.08-MeV photon is 0.424 cm^{-1}.[18] Using these values, photon attenuation in the target materials is found to be 8% for cadmium and 2% for indium. In the case of indium target, the scattering in the target can be neglected, but the effect of scattering in cadmium target is important. Then we made the correction for the flux in the cadmium target as follows;

$$N_{Cd}=N_\gamma\frac{1}{t}\int_0^t\exp(-\mu t')\,dt', \qquad (3)$$

where N_γ is the photon flux incident upon the target, t is the foil thickness, and μ is the total attenuation coefficient of cadmium for 1.30-MeV photon, 0.431 cm^{-1}.[18] Insert-

ing the numerical values for t and μ, the correction factor is found to be 0.963.

The number of photons of energy E_a incident on the target per unit time, unit area, and unit energy, can be expressed as follows

$$N_r=\frac{20}{\pi}\int_{-t}^{t}\int_{-\frac{\pi}{2}}^{\frac{\pi}{2}}\int_{0}^{r_1} a_0 n\frac{d\sigma}{d\Omega}\frac{d\Omega}{dE}\frac{\exp[-(\mu(E_0)r_1+\mu(E_a)r_2)]}{r_3^2}dx d\phi dr, \qquad (4)$$

and

$$\frac{d\sigma}{d\Omega}=r_0^2\left\{\frac{1}{1+\alpha(1-\cos\theta)}\right\}^2\left\{\frac{1+\cos^2\theta}{2}\right\}\left\{1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]}\right\} \qquad (5)$$

where

$$r_0=\frac{e^2}{mc^2}=2.818\times10^{-13}\ \text{cm},$$

$$\alpha=\frac{E_0}{mc^2},$$

E_0 = energy of primary photons (keV),
E_a = energy of scattered photons (keV),
r_1 = distance between the emission point and the scattering point (cm),
r_2 = distance between the scattering point and the boundary of the source cylinder (cm),
r_3 = distance between the scattering point and the target (cm),
μ = total linear absorption coefficient of the material (cm^{-1}),
θ = scattering angle,

and a_0 and n are the same quantities defined in the Yoshihara's formula.

The energy of scattered photons E_a is related to the scattering angle by the well-known formula;

$$\frac{E_a}{E_0}=\frac{511}{511+E_0(1-\cos\theta)} \qquad (6)$$

The factor 20 accounts for twenty ^{60}Co pellets in the irradiation facility and π is the normalization factor for the emitting angle ϕ. The geometrical relation used in this calculation is shown in Fig. 3(b).

The value of E_a is 1078 keV and values of E_0 are 1333 keV and 1173 keV in the case of indium, while those of E_a and E_0 in the case of cadmium are 1300 keV and 1333 keV, respectively. Total absorption coefficients μ used in the present calculation were evaluated by the method reported by Mukoyama.[19] We used the value of the density of stainless steel as 7.75 g per cm^3 and so the electron density of the source material, n, is 2.18×10^{24} per cm^3. The source intensity per unit length a_0 is known to be 4.58×10^{10} photons per sec per cm.[11]

Using these values, the total scattered photon flux N_r was calculated by the electronic computer FACOM M-190 in the Data Processing Center of Kyoto University and found to be

$$\left.\begin{aligned} &N_r=4.80\times10^{3}\ \text{photons per cm}^2\cdot\text{sec}\cdot\text{eV at 1078 keV of }^{115}\text{In} \\ \text{and}\quad &N_{Cd}=8.01\times10^{2}\ \text{photons per cm}^2\cdot\text{sec}\cdot\text{eV at 1300 keV of }^{111}\text{Cd}, \end{aligned}\right\} \qquad (7)$$

where N_{Cd} is the corrected flux mentioned in Eq. (3).

On the other hand, according to the Yoshihara's formula [Eq. (1)], the photon flux in our geometry was estimated as follows;

$$\left.\begin{aligned} &N_\gamma' = 1.53\times10^3 \text{ photons per cm}^2\cdot\text{sec}\cdot\text{eV at 1078 keV} \\ \text{and} \\ &N_{Cd}' = 6.74\times10^2 \text{ photons per cm}^2\cdot\text{sec}\cdot\text{eV at 1300 keV.} \end{aligned}\right\} \quad (8)$$

The values of the flux at 1300 keV are in agreement with each other, but the flux at 1078 keV in our model is three times larger than that of the Yoshihara's model. The reason for this difference is considered to be the effect of the angular distribution of scattered photons. The scattering angle at which 1333-keV photon changes to the energy of 1300 keV is only 8.0 degree, while 1078-keV photons are produced through scattering angles of 24.6 degree by 1333-keV photons and 15.9 degree by 1173-keV photons, respectively.

From these results, we can conclude that in the case of the small-angle scattering, the Yoshihara's model is a good approximation, but his formula cannot be applied to the large-angle scattering event.

IV. RESULTS AND DISCUSSION

Using the observed γ activity resulting from nuclear excitation, we have attempted to evaluate the cross sections for the production of nuclear isomers of ^{111}Cd and ^{115}In by photoexcitation. Induced activity just after the irradiation can be given by the following expression;

$$I_\gamma = N_0 \int N_\gamma(E)\,\sigma_{iso}(E)\,dE \frac{1}{1+\alpha}\varepsilon R[1-\exp(-\lambda_1 t_r)]. \quad (9)$$

The symbols in the expression are

N_0 =the number of target atoms,

$N_\gamma(E)$ =the number of photons incident on the target foil per unit time, unit energy, and unit area,

$\sigma_{iso}(E)$ =the cross section for the production of isomeric nuclei by photo-excitation,

ε =the over-all detection efficiency of the Ge(Li) detector,

R =the branching ratio of the isomeric transition to the ground state,

α =the conversion coefficient of the isomeric transition,

t_r =the period of irradiation by photons,

and

λ_1 =the decay constant of ^{60}Co.

In the case of ^{115}In, the isomeric state decays not only to the ground state of ^{115}In, but to the ground state of ^{115}Sn by β decay, as shown in Fig. 4. The factor R accounts for the β-decay branch. For ^{111}Cd, R is set to be unity. Provided that $N_\gamma(E)$ is a slowly varying function of E, compared with rapidly varying $\sigma_{iso}(E)$, Eq. (9) becomes

$$I_\gamma = N_0 N_\gamma(E_a) \int \sigma_{iso}(E)\,dE \frac{1}{1+\alpha}\varepsilon R[1-\exp(-\lambda_1 t_r)], \quad (10)$$

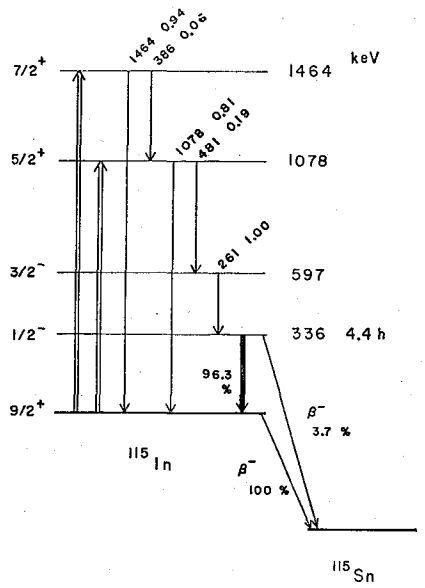

Fig. 4. Partial level diagram of ^{115}In, showing only levels and transitions relevant to the present work. Data are taken from Ref. 14.

where $N_\gamma(E_a)$ is the incident photon flux at resonance. Observed counts of photons from the isomeric state during the measuring period t_m is related to the induced activity I_γ by the following equation;

$$C_\gamma = I_\gamma \exp(-\lambda_2 t_s) \int_0^{t_m} \exp(-\lambda_2 t)\, dt, \tag{11}$$

where t_s is the time elapsed between the end of photon irradiation and the start of measurement, and λ_2 is the decay constant of the isomeric state.

Combining Eq. (10) with Eq. (11), we obtain the integral cross section for the isomer production

$$\int \sigma_{iso}(E)\, dE = \frac{C_\gamma (1+\alpha)\lambda_2 \exp(\lambda_2 t_s)}{N_0 N_\gamma(E_a)\varepsilon R[1-\exp(-\lambda_1 t_r)][1-\exp(-\lambda_2 t_m)]}. \tag{12}$$

The cross section for photoexcitation at the resonance energy $\sigma(E_a)$ can be evaluated from the integral cross section. Using the Breit-Wigner single-level formula for $\sigma(E)$, one obtains

$$\int \sigma_{iso}(E)\, dE = \frac{\pi}{2} \Gamma \sigma(E_a) \frac{\Gamma_{iso}}{\Gamma}, \tag{13}$$

where Γ is the total width of the excited level and Γ_{iso} is the partial width for the transition to the isomeric state from the excited level.

The ^{115}In *nucleus*

From the numerical values listed in Table I and the experimental value of C_γ the integral cross section for the isomer production by photoexcitation is obtained by Eq. (12) as

$$\int \sigma_{iso}(E)\,dE = (1.9 \pm 0.1) \times 10^{-25}\ \mathrm{cm^2 \cdot eV}, \tag{14}$$

as an averaged value of three runs.

This value is compared with the previous experimental values in Table II. The present value is in good agreement with those of Yoshihara[4] and Booth and Brownson,[7] as can be seen from the table. However, if we calculate the photon flux in our geometry according to the Yoshihara's formula [Eq. (1)], our result becomes larger. This means that the value obtained by Yoshihara would be smaller than the present value in more realistic model. The value of Boivin *et al.*[8] is larger than the present value, but owing to large experimental errors of their value, both results are in agreement within experimental errors. The large errors in their results are ascribed to uncertainty in estimation of photon intensity at resonance energy from bremsstrahlung spectrum. The

Table I. Adopted Numerical Constants Used in the Calculation of the Integral Cross Sections for the Isomer Production

	^{111}Cd	^{115}In
the number of atoms ; N_0	3.73×10^{21} a)	6.22×10^{21} a)
the flux of incident photons ; $N_\gamma(E_a)$ ($\mathrm{sec^{-1}\ cm^{-2}\ eV^{-1}}$)	8.01×10^{2}	4.80×10^{3}
the detection efficiency ; ε	$(4.8 \pm 0.1) \times 10^{-2}$ for 245-keV photon	$(3.6 \pm 0.1) \times 10^{-2}$ for 336-keV photon
the branching ratio ; R	1.00	0.963 b)
the internal conversion coefficient ; α	0.0619 c)	1.15 d)
the decay constant of isomeric state ; λ_2 ($\mathrm{sec^{-1}}$)	$(2.32 \pm 0.20) \times 10^{-4}$ e)	$(4.31 \pm 0.06) \times 10^{-5}$ e)

a) Provided that the natural abundance of ^{111}Cd and ^{115}In are 12.75%[20] and 95.67%[21], respectively.
b) Ref. 22. See Fig. 4. c) Ref. 23. d) Ref 22. e) Present work

Table II. Integral Cross Sections for the Isomer Production by (γ, γ') Reaction ($\times 10^{-25}\ \mathrm{cm^2 \cdot eV}$)

	^{111}Cd	^{115}In
Chertok and Booth [6]	0.6 ± 0.2	0.71 ± 0.23
Booth and Brownson [7]	—	1.15 ± 0.4
Boivin *et al.* [8]	$0.8\ ^{+0.4}_{-0.05}$	$3\ ^{+4}_{-2}$
Lakosi *et al.* [5]	1.02 ± 0.26	1.05 ± 0.27
Yoshihara [4]	1.5 ± 0.3	2.3 ± 0.4
Véres [24]	$0.8 \sim 1.5$	$0.9 \sim 5$
Present work	3.5 ± 0.4	1.9 ± 0.1

result of Chertok and Booth[6] is smaller than all other values, but this value has been superseded by the revised value of Booth and Brownson.[7] In conclusion, the present result is in agreement with the previous values.

Taking into account the level scheme shown in Fig. 4, the ratio Γ_{iso}/Γ was determined to be 0.19 from the experimental value of Γ_0/Γ, 0.81, reported by Dietrich *et al.*[25] The total width Γ was calculated from $g\Gamma_0$ obtained by Chertok and Booth[6] together with Γ_0/Γ mentioned above. The factor $g=(2J_1+1)/(2J_0+1)$ is evaluated to be 0.6, where J_1 and J_0 are the spins of the excited level and the ground state, respectively. The value of Γ was found to be $(5.8\pm1.6)\times10^{-4}$ eV.

Inserting these values into Eq. (13), the cross section for photoexcitation at resonance is evaluated to be $(2.1\pm0.6)\times10^{-22}$ cm^2.

The ^{111}Cd *nucleus*

The integral cross section was determined to be

$$\int\sigma_{iso}(E)\,dE=(3.5\pm0.4)\times10^{-25}\ \text{cm}^2\cdot\text{eV}, \tag{15}$$

as an averaged value of 21 runs.

In Table II, the experimental results of $\int\sigma_{iso}dE$ are shown. Our experimental value is slightly larger than other values. The possible reason of this difference is considered to be the incident flux of scattered photons, because the photon flux calculated from our model is sensitive to the energy of scattered photons through the scattering angle. This is contrast to the Yoshihara's model, where the photon flux does not so much depend on the energy. The present value was obtained by assuming the excited level to be 1300 keV. A different choice for the excitation energy leads to change in the photon flux corresponding to the excited level and results in variation of the cross section.

For the ^{111}Cd nucleus, there have been a little amount of informations about the width of the excited level and the branching ratio to the isomeric state. In order to evaluate the cross section for photoexcitation at resonance $\sigma(E_a)$, we need some assumptions. In the present work, we calculated this cross section, based on the following assumptions; (1) the total width of the excited level Γ is expressed as a sum of the partial width for the direct transition to the ground state Γ_0 and that for the transition to the isomeric state Γ_{iso}, and (2) the value of the spin of the excited state is 5/2.

The value of the partial width $g\Gamma_0$ was measured by Chertok and Booth[6] as $(1.7\pm1.1)\times10^{-3}$ eV. From the assumption (2) and the value of the spin of the ground state 1/2,[13] we obtained $g=3$ and $\Gamma_0=(5.7\pm3.7)\times10^{-4}$ eV. The ratio Γ_{iso}/Γ_0 was determined to be 0.088 from the experimental value of the integral cross section and $g\Gamma_0$ by using the following equation;

$$\int\sigma_{iso}(E)\,dE=\frac{\lambda^2}{4}g\frac{\Gamma_0\Gamma_{iso}}{\Gamma}, \tag{16}$$

where λ is the wave length of the photon with the resonance energy, provided that the energy of the excited level is 1300 keV. The total width was estimated as $(6.3\pm4.1)\times10^{-4}$ eV from the values of Γ_0 and Γ_{iso}/Γ together with the assumption (1).

Inserting these values of Γ_{iso}/Γ and Γ into Eq. (13), the cross section $\sigma(E_a)$ was

evaluated to be $(3.5\pm2.3)\times10^{-22}$ cm^2. This value is based on many assumptions as described above. For ^{111}Cd, further studies on various nuclear parameters, such as accurate energy of excited level, total level width of excited state, and branching ratio of the transition to the isomeric state, are hoped.

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